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# ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

REPORT No: MET.54

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# SOME METALLOGRAPHIC OBSERVATIONS RELATING TO THE FATIGUE OF METALS

by

P.J.E.FORSYTH, A.I.M.

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Report No.Met.54

June 1950

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Some metallographic observations relating to the fatigue of metals.

by

P.J.E. Forsyth, A.I.M.

R.A.E. Ref: Mat.M/10187/PJEF/11

SUMMARY

Observations have been made on the microstructure of metals subjected to fatigue stresses. The changes observed include the appearance of deformation bands and crystallites in the original grains.

A modification of the fatigue process occurs at high stresses where the rapid formation of crystallites causes a widespread disturbance of the grains.

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## 1 Introduction

Existing theories of fatigue assume that the process of work hardening takes place on the slip planes of the metal crystals until cracking occurs if the stress is sufficiently high. No distinction has been drawn between fatigue at high and low stresses as it has been assumed that the deformation was associated with slip alone; the degree of stressing would then only control the rate of work hardening and the fatigue life of the specimen. The characteristic shape of the fatigue curve for a metal might suggest that two mechanisms were in operation, but the complex nature of the strain hardening process has provided an alternative explanation. Orowan[1] has pointed out that the slope of the steep part of the logS log n curve obtained by theoretical considerations based on the rate of work hardening of plastic regions within the metal crystal is approximately 1 while that obtained from actual fatigue tests is rarely greater than 0.5. Here again, the complexity of the mechanism of strain hardening and the over simplification of the function by the use of a static strain hardening coefficient has been realised.

Gough[2] has metallographically examined different metals, mainly in the form of single crystals, and has concluded that the process of fatigue is one of strain hardening by slip on the operative glide planes of the crystals until cracks occur on these planes. From this he has concluded that the strain hardening process is identical with that of a crystal subjected to a static stress. He resolves the problem of fatigue cracking into one of cohesion between the metal atoms which will only be solved when the complete theory of static rupture strength has been evolved. Gough has also suggested that slip is accompanied by fragmentation of the original metal crystal into small crystallites in the region of the planes where slip has occurred, and that these crystallites suffer a slight rotation or re-orientation from the original crystal direction. More recent evidence of crystal break-up under stress has been put forward by Wood and Rachinger[3], Cahn[4], and others.

In the present work a study has been made of crack formation and propagation in a high purity Aluminium - 1% Silver alloy, commercial purity copper, and Armco iron, the majority of the tests having been made on the first mentioned material. Alloys of the Aluminium-Silver system had already been selected for a creep investigation being undertaken in the Department in view of the range of solid solubility of silver in aluminium being convenient for the study of the properties of single phase and duplex structures, and because of the similarity in size of the Aluminium and Silver atoms and the negligible solid solution hardening resulting from this. For the same two reasons the Aluminium-Silver system offers a convenient range of alloys for the study of fatigue.

The observations were made in small polycrystalline specimens, the work of Gough and others having established the close identity of the mode of failure in single and polycrystalline specimens. To allow continuous examination of the specimens while undergoing fatigue tests the technique described in R.A.E. Report No.Met.39 was employed, using stroboscopic illumination. The specimens were vibrated until, in most cases, failure in the form of cracking occurred. As the alloy had a very low proof stress it tended to creep during the test and thus upset the vibrator setting. This was overcome by the provision of a spring to oppose the pull of the electromagnet thus in effect making it a constant strain machine.

## 2 Heat treatment and preparation of specimens

Aluminium ½% Silver alloy: Cold rolled to specimen thickness of 2 mm from ⅝" diameter extruded bar, machined, and then heat treated for 1½ hours at 465°C followed by a cold water quench. The grain size was approximately 0.2 mm diameter.

Commercial copper: Cold rolled to specimen thickness from ½" diameter bar, machined, and then heat treated for 2 hours at 800°C in a nitrogen atmosphere. (This heat treatment produced a grain size approximately equal to that of the Al-Ag specimens).

Armco iron: Cold rolled to specimen thickness from ¼" plate. Annealed for 2 hours at 900°C in nitrogen atmosphere.

The specimens were all electropolished without any grinding operation after the annealing treatment to ensure that no worked surface layer existed. They were tested in the polished condition so that surface movement, such as slip, could more readily be detected. After testing, they were etched. The reagents found most suitable were:-

| | |
|---|---|
| Aluminium - ½% Silver alloy | - 50% HF in water followed by a conc. $HNO_3$ cleansing dip. |
| Commercial copper | - $FeCl_3$ + HCl in alcohol |
| Armco iron | - 2% Nital |

## 3 The effect of the surface film formed during electropolishing on the appearance of the fatigued specimen

This has been the subject of a recent paper by Wilms[4]. We have also observed the marked effect of a surface film formed on the Al ½% Ag alloy during electropolishing of the specimens. This film could, however, be readily removed by short dip in the etching reagent described above for this material. On investigating the effect of this film on the surface appearance of a fatigued crystal, it was found that the film greatly impeded the appearance of slip bands, whereas a specimen with the film removed showed fine slip bands after the slightest deformation. In fact, the large number of slip bands in the latter specimens obscurred the detail of other forms of deformation which was observed on specimens fatigued with the film in situ. Repolishing to remove the slip bands revealed again the forms of deformation which had occurred and which will be described later.

## 4 Microscopic examination of materials before testing

Aluminium ½% Silver specimens: The structure consisted of a complete solid solution of equi-axial grains and was practically free from particles with the exception of a few isolated stringers, which did not interfere with the observations.

Copper specimens: These consisted of twinned equi-axial grains.

Armco iron specimens: These consisted of equi-axial recrystallised grains. A few residual grain boundaries suggested that a much longer annealing time would be required to completely remove traces of the former structure.

## 5 Distortion produced by static stresses

Figure 1 shows the appearance of slip bands produced by static stresses. The shear displacement on the slip planes can be clearly seen at the edge of the specimen. This represents the classical idea of glide on the operative slip planes. Although these slip bands are sharply defined at X1500 magnifications they are generally considered to be many atomic planes thick. According to Tammann[6] the only possible means of deformation is by slip or twinning, but recent work has shown that other forms of deformation may occur. Elam[7] has shown that deformation in $\beta$ brass does not take place by slip on any definite crystal plane but is brought about by movements of a complicated nature. These movements produce bands in the crystal some having a different orientation to that of the original crystal and others thought to be layers of more highly strained material. A mechanism of deformation termed 'Kinking' has been described by Orowan[8], and he considers that there are many indications that deformation bands in metals hitherto considered glide or twin bands may be in reality 'Kink' bands. The mechanism of flexural glide either with or without accompanying relaxation in the form of polygonisation[4] can also be considered as a possible form of deformation. The result of any of the latter forms of deformation will be local variations in orientation, whereas pure glide will cause no such change. These variations may be very small and difficulties in detection may therefore be experienced.

Possible methods of revealing local variations in orientation by metallographic means include, (a) by detecting differences in surface level on the polished surface (b) by preferentially etching areas having a different orientation, or (c) by the use of an etching reagent which is sensitive enough in its attack to reveal boundaries where the difference in orientation between adjacent areas is very small.

The second method will produce 'stepped' boundaries, and although the difference in level may be very slight it could in the present investigation be revealed by stopping down the light source and thus reducing the effective numerical aperture of the microscope objective. The effectiveness of the third method will depend on the differences in orientation at the boundaries. Lacombe and Beaujard[9] have shown that the etching effect becomes negligible if the difference in orientation is only about 1° or less. Lacombe has used reagents which produce etch pits to reveal these 'difficult' boundaries, the boundaries being outlined by these pits.

## 6 Distortion effects produced by cyclic stresses

Ewing and Humphrey[10] were the first to make a study of the microstructural changes brought about by cyclic stressing. Their observations led them to suggest an "attrition" theory of fatigue in which the repeated applications of an unsafe stress produced repeated slip resulting in attrition of the slip planes, this attrition eventually led to cracking and ultimate failure. This suggests that if slip occurs then ultimate fracture must follow, but it has been found in the present series of tests that appreciable plastic deformation occurs even at stresses below the safe range estimated on a basis of $150 \times 10^6$ cycles. Strain hardening occurs below and above the fatigue limit, suggesting that slip is not a weakening process and therefore the attrition theory does not seem tenable. For example specimens of the Aluminium ½% Silver alloy has been fatigued at a certain stress for more than $150 \times 10^6$ cycles and many slip bands were apparent after this treatment but no additional slip bands or signs of cracks were observed suggesting that the slip process had hardened the material sufficiently to make it resistant to further slip at that particular stress. Under these

conditions it would appear that the material would not deteriorate further. Specimens fatigued at slightly higher stresses showed more marked slip, and one which failed after $150 \times 10^6$ cycles is shown in Figure 2. In the as polished and fatigued condition the specimen differed from the previous one in the number of slip bands present and in their more marked appearance in the region where failure had occurred. If both specimens were electropolished, however, the slip bands were removed leaving a featureless surface. Etching this surface revealed deformation bands and small crystallites in the specimen which had cracked, although none could be detected in the uncracked specimens. The deformation bands were very clearly defined in some cases, see Figure 3, but were more usually irregular. These bands seem to coincide with the surface striations which were observed in specimens fatigued at higher stresses with the polishing film still in situ. It seems now that these striations were deformation bands which had been rendered apparent by the absence of slip bands on the surface. The normal light microscope working with a greatly reduced N.A. is extremely sensitive to differences in level of the surface of a highly polished specimen. A fringe pattern of a crystal containing these striations is shown in Figure 4. From the pattern it can be seen that the striations are of a corrugated or undulating nature, the difference in level from crest to trough being about $0.3\mu$. The usual slip bands as produced by static stressing show as sharp steps in the fringe pattern and would therefore be clearly distinguishable from these striations. Fatigue tests were made at various stresses and it was found that as the stress was increased more marked deformation bands appeared, and the slip which appeared marked near the fatigue limit now seemed to be of secondary importance. In specimens with the surface film no slip bands appeared except at the lower stresses, although tests made with the film removed showed that they were produced at all stress levels. It seems from this that an annealed crystal will slip freely until it has been sufficiently hardened by this slip. If, however, the stress is high enough for the formation of these deformation bands the slip process is greatly impeded and becomes a secondary process. Tests made on specimens at the higher stresses showed that these deformation bands gave way to an even larger scale deformation. Figure 5 shows these striations and Figure 6 shows the more widespread deformation which occurs at the higher stresses, this surface having been repolished to remove the marking slip bands and then etched. The ridges and furrows which occur in this type of deformation often run along, or parallel to, the grain boundaries and are not associated with the crystal planes. From this it can be seen that three forms of deformation are occuring and the predominance of any one will depend on the stress level at which the material is being fatigued. Earlier it was shown that these deformation bands could be revealed by etching because of the slight differences in orientation that exist in the crystal. It can be seen from Figure 6 that the deformed areas consist of many small crystallites; the new boundaries of these crystallites are more clearly shown in Figures 7 and 8 and appear to follow the contours of the ripples, as can be seen in Figure 8. The widespread deformation seems, therefore, to be associated with the formation of crystallites, the process of crystallite formation allowing further deformation to occur.

Fatigue tests on copper specimens have shown that slip is very marked as is also crystallite formation, especially when associated with the slip planes. At the higher stresses a more general form of deformation with small very clearly defined crystallites is also observed. It would seem therefore that both the Aluminium-Silver alloy and copper behave in much the same way when subjected to cyclic stresses.

Figures 9 and 10 show crystallites associated with slip bands, and Figure 11 shows the more deeply etched crystallites which occur at the

higher stresses. All the copper specimens showed a marked mosaic pattern which can be seen in the background. This was only revealed in the material that had been subjected to cyclic stressing. Figure 12 shows the mosaic pattern produced at a low stress level, the higher stresses producing a finer mosaic. The Armco iron specimens showed similar crystallite formations to those observed in the Aluminium - ½% Silver alloy specimens. A typical region of crystallites is shown in Figure 13 The surface of Aluminium - ½% Silver specimens after fatiguing at a high stress level are shown in Figures 14-16. The cellular network pattern which was often observed on the polished surface after being fatigued is shown in Figures 14, 15 and 16. It can be seen that the cellular structure appears in areas of crystallite formation and that some small crystallites presumably of a favourable orientation for slip show this structure very clearly. The specimen shown in Figure 14 was fatigued, repolished, and etched to reveal the crystallites. The repolishing and etching treatment removed all evidence of the cellular pattern but after further fatiguing it reappears in certain crystallites indicating that further deformation, and possibly further crystal breakdown was occurring. Figure 15 shows an area of this structure at a higher magnification from which it can be seen that appreciable differences in orientation occur throughout the area. Some of these areas differ in orientation by as much as 10°.

## 7 Boundary movement

A noticeable effect of the fatigue stresses on the structure was the movement of grain boundaries. Thus, boundaries which were initially invariably straight or smoothly curved, were of irregular shape after being fatigued. This is shown in Figures 17 and 18 where it can be seen that the irregular nature of the boundary is associated with the deformation bands which were present in Aluminium - ½% Silver alloy specimens. Figure 19 shows a similar effect in Armco iron. It was noticed that the effect was more marked if the difference in orientation between the adjoining grains was small.

## 8 Crack formation and propogation

Figures 20-23 show the initiation and progress of fatigue cracks in an Aluminium ½% Silver alloy specimen. This specimen was fatigued at a low stress level where only the localised form of crystallite formation occured. The first cracks appeared after about $10 \times 10^6$ reversals. Figure 24 shows cracks at X2000. It can be clearly seen that the cracks are irregular as though they follow small crystallite boundaries.

Fatigue and crack formation in alloys at higher stress levels is however a different process. Figure 25 is a schematic series of diagrams showing the sequence of events leading to the formation of a crack at a high stress level in the Aluminium - ½% Silver alloy. The features observed in the final stage are shown in Figure 26 in which the root of the crack is seen to be progressing through a region of crystallites. In the copper specimens the formation and propogation of cracks was nearly always associated with the twin bands as shown in Figure 27.

## 9 Reverse bend tests

It was thought that a few reversals of bending of a large strain amplitude might produce similar changes as the fatigue stresses had done. The form of specimen used in the fatigue studies were used for these tests. The Aluminium - ½% Silver alloy specimens were given one or more reverse bends of ±10° and examples of the microstructures after bending are shown in Figures 28 and 29. After bending the specimens

were repolished to remove the slip bands and then etched. It can be seen from Figures 28 that after only 2 bends a number of deformation bands have appeared. The difference in orientation of the bands from the remainder of the crystal can be seen very distinctly where different degrees of grain boundary etching are visible at the ends of the bands. This effect is similar to that sometimes found where twin bands meet a grain boundary.

Further reverse bends resulted in the more or less continuous bands breaking up into a number of fairly well defined crystallites very similar to those observed in the fatigue tests. This is shown in Figure 29.

Reverse bend tests on copper specimens produced many small clearly defined crystallites, again similar to those found in the fatigued specimens.

## 10 The strain/logN curve for Aluminium ½% Silver alloy

The observations made on the Aluminium - ½% Silver specimens have indicated the change in mode of deformation which occurs under different degrees of cyclic strain. Diagram I shows a curve in which the total deflection of the specimen has been plotted against endurance. The experiments show that deformation by a system of bands is confined to the lower stresses, and that deformation by a more general crystallite formation occurs on the steeper part of the curve, the change from one form to the other occurring at the 'Knee' of the curve. At strain amplitudes corresponding to this region combinations of the two forms of deformation are present. From these observations it was possible to state in general terms the fatigue conditions to which a particular specimen had been subjected.

## 11 Discussion

In a metallographic study of the effect of cyclic strain in a number of metals slip bands have been observed at all stresses where plastic deformation occurs. At high stress levels the slip is accompanied by deformation bands of a different orientation from the surrounding lattice. On the basis of the observations made it might be inferred that this change from pure slip to deformation bands occurs when the 'safe range' for the metal is exceeded. Certainly an Aluminium - ½% Silver specimen which failed at $150 \times 10^6$ cycles showed deformation bands. No such bands could be detected on specimens which had been subjected to lower stresses without causing failure, although slip bands had been apparent on these specimens. Whether deformation bands would appear at some extended time it is impossible to say. The observations do not preclude this possibility as the bands are not necessarily produced instantaneously but may be produced after many repetitions of strain on certain slip planes. Reversals of a high strain value may very rapidly produce deformation bands as was found after 2 reverse bends, but in the case of the longer life specimens it seems to be a more prolonged process of deformation. These bands resemble twin bands, and it seems significant that cracking starts at these bands while copper which exhibits annealing twins is prone to cracking along twin bands. These deformation bands eventually break up into small crystallites so that cracks which form and follow their boundaries are of an irregular nature.

The deformation characterised by bands of crystallites formed at the slip planes is localised in the sense that no large scale movement of the crystal lattice is involved. It is in this respect that the difference in behaviour of the higher stresses becomes most apparent i.e. where large scale movement of the metal is observed. The reason

for this difference is not yet understood, but the higher degree of plastic strain per cycle would be expected to produce a more widespread deformation, although time also may be an important factor. The continuous formation of crystallites under high cyclic strain appears to allow a general plastic movement of material presenting the appearance showing in Figure 6. Such deformation might possibly be related to that shown by Wood to occur under creep stresses. This general deformation eventually leads to the formation of a deep groove and at a later stage, a crack develops. The formation of this groove and the increased surface area taken up by the formation of undulations suggests that the deformation under cyclic loads is greater during the tension part of the cycle. Continuous crystal breakdown in the hollows will cause a deepening groove and eventually a crack. This sequence is shown in Figure 25. The region of crystal breakdown precedes the root of the crack, as has been described earlier. Thus it seems from the observations made that fatigue is not a simple strain hardening process but is complicated by the formation of deformation bands and crystallites within the metal crystal. This phenomenon is most marked at high stress levels and permits a continuous plastic movement to occur while it is in progress. It may eventually initiate a crack by forming a groove, and all crack progress appears to be associated with the formation of a zone of crystallites ahead of the root of the crack. Until more is known about the mechanical properties of such an aggregate of small crystallites it is not possible to estimate their effect. If they are softer than the surrounding grains it may be that the stress concentration at the root of a crack entering such a zone is lower than that estimated from elastic theory, and this may account for the observations that some cracks progress a certain distance and are then overtaken by other cracks which are formed later. The presence of the crystallites may also contribute towards prolonging the life of the specimen by deflecting the crack into a direction parallel to that of the applied stress and thereby reducing its effectiveness as a stress raiser. The presence of branch cracks at the root of the main crack may also help to dissipate the stress concentration in this region.

## 12 Conclusions

Three materials have been examined under fatigue stresses, Aluminium - 5% Silver alloy, copper and Armco iron.

All the tests have shown that fatigue cracking is preceded by some form of crystallite formation.

Slip bands appear at all stresses down to well below the fatigue limit.

Deformation bands, which appear to be regions having a slightly different orientation to that of the parent crystal, were observed after 2 reverse bends of a large strain amplitude. At lower strains the bands were observed to be formed in regions of slip, the process taking a relatively long time. It is these deformation bands which later break up into crystallites.

At the higher strain amplitudes a more widespread crystal breakdown occurred with extensive crystallite formation. This process allowed marked disturbance of the surface material into folds or undulations. Cracking in this condition was preceded by a continuously deepening groove, and the cracks progressed into a region where crystallite formation had occurrdd. This was also true of the tests conducted at lower stresses in which a crack had formed, because the high stress concentration at the root of the crack produced crystallite formation.

Copper exhibited a 'mosaic' background structure when etched after fatiguing. The degree of fineness of this mosaic seemed to depend on the stresses involved. Near the point of fracture the mosaic structure could only just be resolved.

Examining these structures in relation to the strain/logN curve it has been found in the Aluminium - 4% Silver alloy that the change in the slope of the curve coincides with the change in type of deformation.

Marked modification of the grain boundary was often observed where the difference in orientation between neighbouring grains was slight, especially at the ends of deformation bands.

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Attached: Drawings - Mat.9547
Negatives - 88175 - 88180

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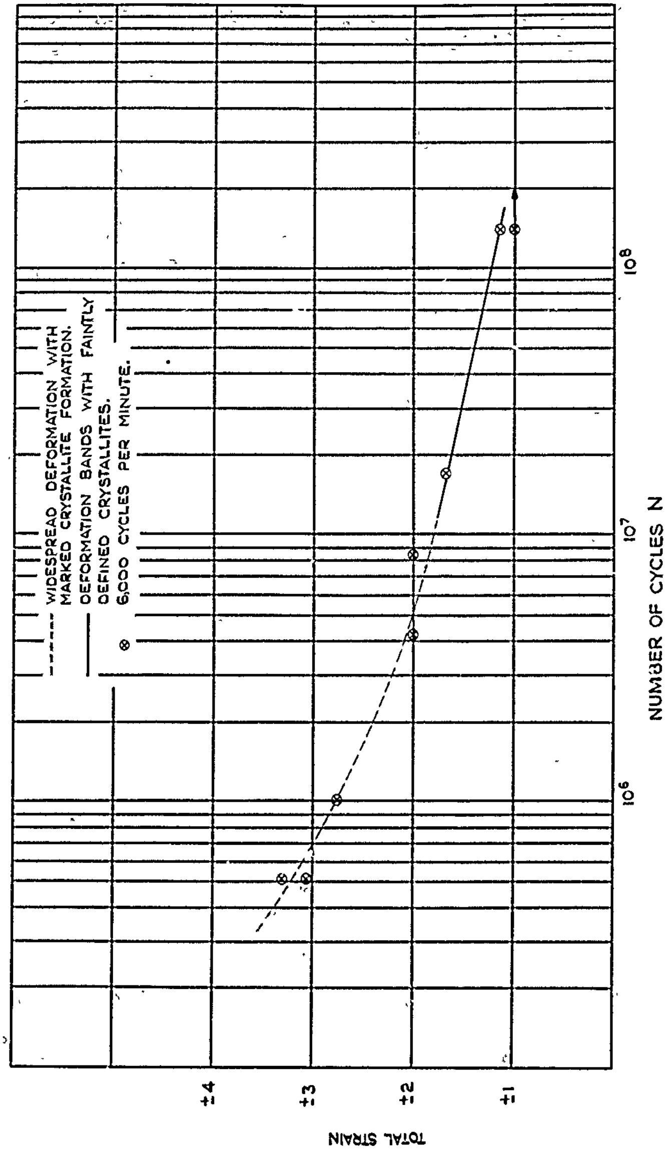
FIG. I.


WIDESPREAD DEFORMATION WITH MARKED CRYSTALLITE FORMATION.
DEFORMATION BANDS WITH FAINTLY DEFINED CRYSTALLITES.
6,000 CYCLES PER MINUTE.
10^6
10^7
10^8
NUMBER OF CYCLES N
±4
±3
±2
±1
TOTAL STRAIN

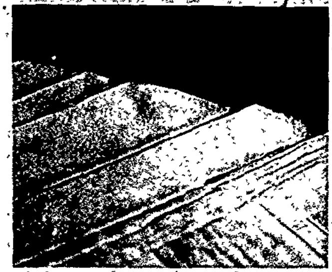


FIG.1 ×1500

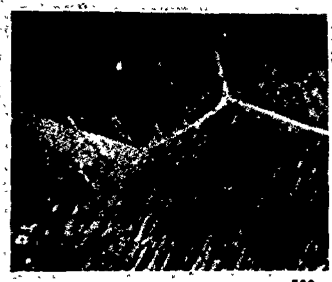


FIG.2 ×500

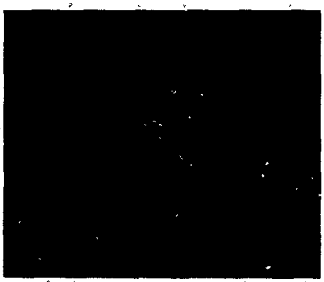


FIG.3 ×500

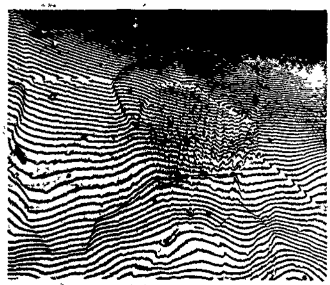


FIG.4 FRINGE PATTERN λ 5460 Å ×100

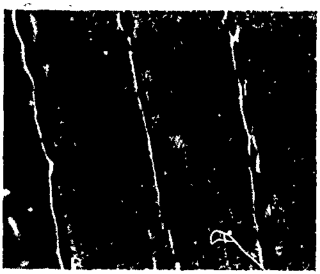


FIG.5 ×1500

FIG.6 ×200

FIG.7 x1000

FIG.8 x500

FIG.9 x1000

FIG.10 x1000

FIG.11 x1500

FIG.12 x1500

FIG. 13 ×1500

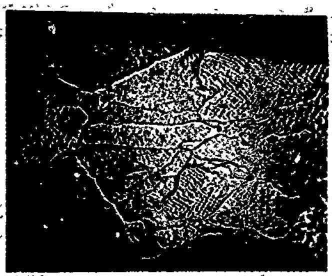


FIG. 14 ×500

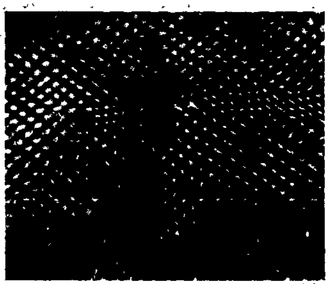


FIG. 15 ×1500

FIG. 16 ×200

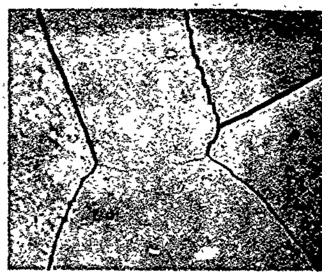


FIG.17 ×500

FIG.18 ×1500

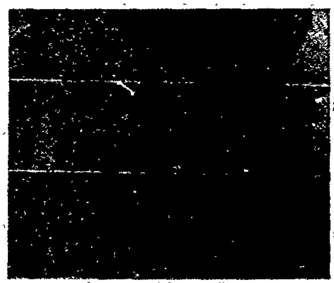


FIG.19 ×1000

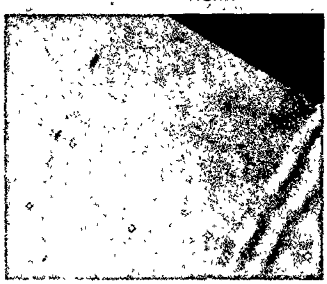


FIG.20 ×500

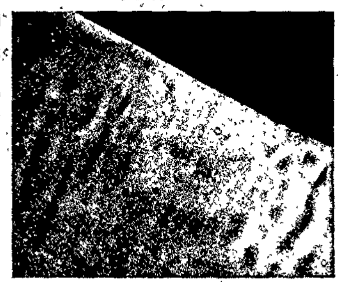


FIG.21 ×500

FIG.22 ×500

FIG.23 ×500

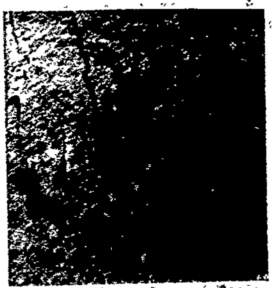
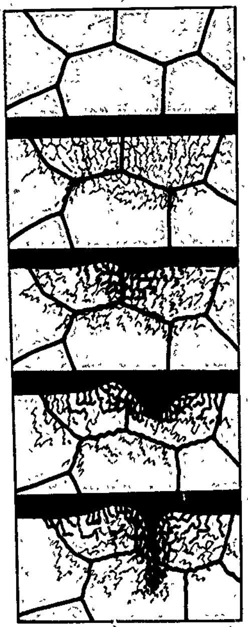


FIG.24 x2000



1. ORIGINAL ANNEALED GRAIN STRUCTURE

2. BREAK-UP OF GRAINS INTO SMALL FAINTLY DEFINED CRYSTALLITES

3. THE APPEARANCE OF MORE SHARPLY DEFINED CRYSTALLITES WITH FLOW OF THE METAL NEAR THE SURFACE

4. MORE WIDESPREAD CRYSTALLITE FORMATION AND AN INCREASE IN THE MAGNITUDE OF THE CORRUGATIONS

5. THE FORMATION OF A DEEP GROOVE WHICH EVENTUALLY INITIATES A CRACK. A REGION OF CLEARLY DEFINED CRYSTALLITES PRECEEDS THE ROOT OF THE CRACK

FIG.25

THE SEQUENCE OF CHANGES OCCURRING IN THE STRUCTURE OF AN ALUMINIUM 1% SILVER ALLOY WHEN SUBJECTED TO HIGH CYCLIC STRESSES

FIG.26 x1500

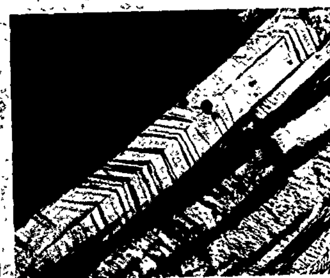


FIG.27 x500

FIG.28 x1000

FIG.29 x1000

dstl

[dstl]

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